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REDUCTION OF LIQUEFACTION SUSCEPTIBILITY UNDER EXISTING STRUCTURES BY PERMEATION GROUTING

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ABSTRACT

1999 Izmit earthquake has shown that a vast number of buildings were built over liquefiable silty soils in Adapazari, Turkey. Most of these buildings have been classified as "moderately" damaged, and mitigation of the liquefaction risk has been made mandatory before these structures are reoccupied. A literature review revealed that low pressure permeation grouting has been used successfully for this purpose. The effectiveness of this method is investigated in this study through geophysical measurements before and after the soil improvement at four different sites in downtown Adapazari .

The results of this study indicate that the shear wave velocity of the improved soil is increased approximately twofold and the shear modulus of the improved soil is increased more than threefold. Improvements imparted to the soil are sufficient to reduce the liquefaction risk substantially. These findings are in line with the results reported in the literature. It appears that low permeation grouting is capable of reducing liquefaction risk under existing structures rapidly and at low cost.

INTRODUCTION

During the earthquake of 17 August 1999, it was observed that significant portion of the city of Adapazari, Turkey as had experienced liquefaction. As a result, most buildings in zones where weak silts and and silty sands are abundant had undergone the detrimental effects of liquefaction. Although the general description of the problem appears to be "soil failure," the problem may be best defined by liquefaction, bearing capacity failure, and excessive deformations of soft clays causing excessive settlement and tilting of structures as a result of the cyclic loading. In order to reuse these buildings, provisions must be taken against soil failure. The thickness of the sediments in downtown Adapazari exceeds 1,000 meters, and the upper 5-7 meters are young (750±100 years) and their properties dominate the earthquake behaviour of the existing structures.

1997 Turkish specification for structures to be built in disaster areas classifies the foundation soil in four groups of A, B, C, and D. Group A and B type soils have high shear wave velocity and include soft rocks, soft rocks/hard soils, overconsolidated clays and dense sands and gravels. Group C type soils are more like transition soils between strong soils (Group A and B) and weak soils (Group D) depending on the shear strength, earthquake magnitude and structural properties.

Group D soils characterize young alluvial soils whose shear wave velocities are less than 200 m/s with SPTN values below10. This grup of soils have low bearing capacity and experience soil amplification, liquefaction, and show excessive settlements in an earthquake. In Adapazari, Turkey, over 90% of the top 6-m soils belong to this group. The main objective of soil improvement may thus be defined to change the soil classification from Group D to higher groups.

Soil improvements for sites without any building can be achieved by constructing engineered fill, pile applications, sheet pile walls, stone columns, jet grout columns, vibroflotation, and similar methods (Kramer, 1996 and ISSMGE, 1996).

Improving the soils under existing structures is more challenging. Limited overhead in the basement of buildings eliminates the use of most these methods. Cost of alternative improvement methods such as reinforced concrete mini piles is high when compared to the cost of the replacing the buildings.

In this study, effectiveness use of permeation grouting under existing structures in Adapazari and environs is investigated through geophysical investigations, and the findings are presented.

GEOMORPHOLOGY OF ADAPAZARI

Soils in downtown Adapazari exhibit unique behaviour because of the very thick alluvial sediments (over 1,000m) and weakness of these soils. Topography is flat with average elevation of 30m above MSL, and the ground water table fluctuates between 0 and 3 meters from the surface, depending on the regimes of Sakarya River to the north and the Cark stream and Lake Sapanca to the west (Fig. 1).

Geologic investigations have shown that the river and the stream that run though the downtown area caused frequent flooding resulting in lake and subsequently marshland formation (Bol,2003). During these events rapid sedimentation took place, and heterogeneous soil layers, both in vertical and in horizontal directions, formed. Hydraulic conductivity of the silty and clayey deposits varies between 10^{-5} and 10^{-7} cm/s, depending on the existence of thin sand layers. Normally loaded silts,sandy silts and clays are abundant near the surface underlain by moderately overconsolidated clays and medium dense to dense sands. Almost all soils fall in Group D category as described above.
Widespread ground failure attested to the inferiority of the surficial layers.

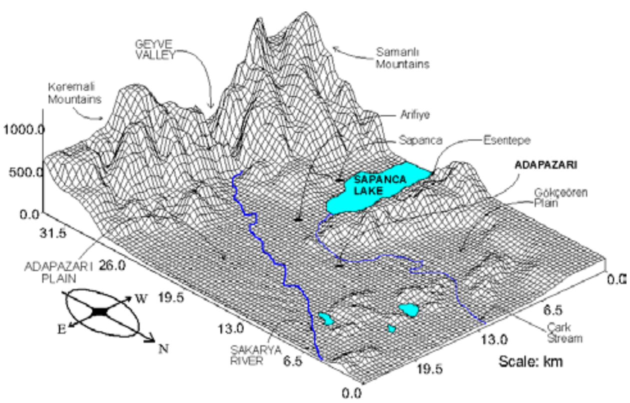

Fig. 1. Geomorphology of Adapazari (Onalp et al., 2000)

SOIL IMPROVEVEMENT BY CEMENT INJECTION

Cement injection is mostly used to reduce the permeability of soils and to improve the shear strength of soils, and has cost advantage over chemical stabilization methods. Generally, a cement/water mixture under high compression is pumped into the soil where it sets and forms hardened lumps. When it is used to prevent ground failure, vertical cement columns are created, which can improve the overall soil quality from Group D to Group C or Group B.

Low pressure permeation grouting has been shown to be useful when used for improving the soil properties against liquefaction (Towhata and Kabashima, 2001). The researchers tested undisturbed samples obtained before and after the application. Dynamic triaxial tests and shake table tests were conducted and it was found found that liquefaction resistance of the soils are significantly improved by low pressure permeation grouting.

In a field application, the effectiveness of low pressure compaction grouting has been investigated under a 3350m^2 warehouse building in San Francisco, USA. Injection wells were made on 1.85m square patterns, and for each meter of well 0.3 m^3 of cement/water mixture were injected up to a depth of 10m. , SPT N values after the application were reported to have increased to around 20 from pre application values of around 10 (ISSGE-TC4, 2001). The water table was reported to be 1.0-2.4m below the surface.

In Adapazari,Golcuk and Yalova, Turkey, low-pressure (3 bar) permeation grouting applications have been used in approximately ten public and private sites. In these sites, 10-m grout wells were made with 2 to 3 meter spacing between the two adjacent wells. A mixture with water-cement ratio of 1:1 was used, and the injections started at the bottom of the well and rose toward the surface with 0.5 to 1 meter intervals. Approximately 0.15m^3 of water-cement mixture for each meter of the well were allowed to penetrate into the soil. Because of the high water content in the soil, sodium silicate was added into the mixture as accelerator, and trisodium phosphate was added to improve the viscosity . Because the soils are very soft and their permeability is low, these applications resulted in lumps of mixture stacked on one another, creating irregularly shaped columns as verified by excavations after the applications. When sand layers were encountered, grout intake increased significantly, and it was observed that the grout occasionally escaped through the sand layer beyond the building area. This has been compensated by raising the injection nozzle faster than the targeted speed, thereby eliminating excessive loss of grout in the sand layer. Overall, low permeation grouting was deemed to be satisfactory.

PRACTICE OF INJECTION

As presented above, low permeation grouting is verified to be reliable and economical for soil improvement under existing structures. Four applications made in Adapazari are presented below.

Research sites and soil properties

Donergecit building is located in the Tigcilar Neighborhood of Adapazari (Fig. 2). According to the boring log made prior to the injection, the top 30 cm is fill; following layer between 0.3m-5.5m is clayey silt, and the subsequent layer between

In Adapazari and Yalova, Turkey, low-pressure (3 bar) permeation grouting applications have been used in approximately ten public and private sites. In these applications, 10-m grouting wells were made with 2 to 3 meter spacing between the two adjacent wells. Water-cement mixture of 1:1 was used, and the injections started at the bottom of the well and rose toward the surface with 0.5 to 1 meter intervals. Approximately $0.15m^3$ of water-cement mixture for each meter of the well were allowed to penetrate into the soil. Because of the high water content in the soil, sodium silicate was added into the mixture as accelerator, and tri sodium phosphate was added to improve the mixture flow. Because the soils are very soft and their permeability is low, these applications resulted in lumps of mixture stacked one another, creating irregularly shaped columns as verified by excavations after the applications. When sand layers were encountered, grout intake increased significantly, and it was observed that the grout has reached through the sand layer beyond the building area. This has been compensated by raising the injection nozzle faster than the targeted speed, thereby eliminating the excessive loss of grout in the sand layer. Overall, low permeation grouting is deemed to be satisfactory.

EFFICACY OF CEMENT INJECTION

As presented above, low permeation grouting is verified to be reliable and economical for soil improvement under existing structures. Below four applications made in Adapazari are presented.

Test sites and soil properties

Donergecit building is located in the Tigcilar Neighborhood of Adapazari (Fig. 2). According to the boring log made prior to the injection, the top 30 cm is fill; following layer between 0.3m-5.5m is clayey silt, and the subsequent layer between 5.5m-15.0m is silty sand. The water table is 1.4m below the surface.

Karaosman building is also in the Tigcilar district of the city where liquefaction was widespread in the 1999 earthquake. Soils layers from top to bottom are as follows: between 0 to 1m organic soil, between 1m to 6.5m is sand, between 6.5m to 9m is clay, between 9m to 11 m is silt, and between 1m to 15m is sand and the water table is located 0.4m below the surface.

Aydin business center is located on Kavaklar Street in Tigcilar district. Soils layers from top to bottom are SM between 0 to 2m, ML between 2m to 12m, and CH between 12m to 15m.

Atagun business center is located in the Yenicami neighborhood (Fig. 2). According to the two borings made prior to the injection, the top 4.5m layer is ML, following layer between 4.5m and 9m is SW-SM, next 1m is CL, and the following 5m is ML. The groundwater level was measured in December, and was found to be 1.9m below the surface.

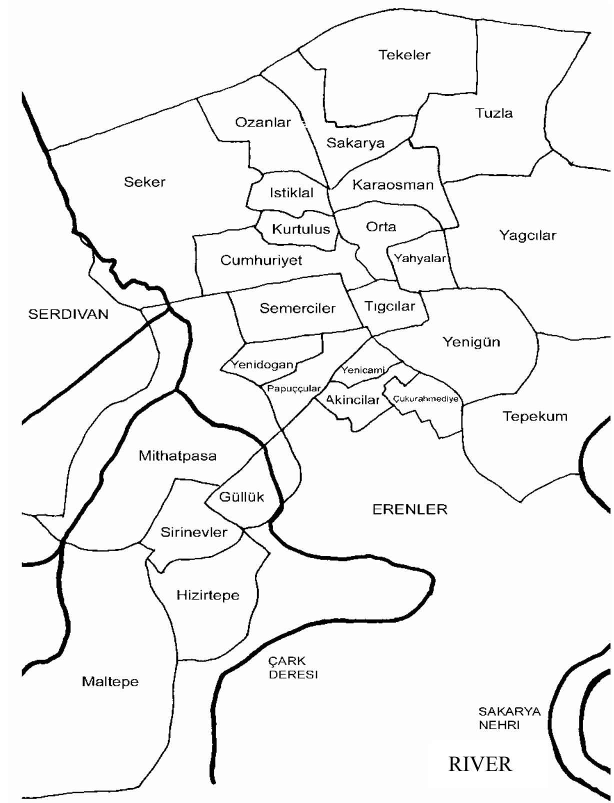

Fig. 2.Districts of Adapazari, Turkey (Onalp et al., 2000).

SPT N values for all four locations are tabulated in Table 1. The table indicates that the top 5m in all sites is very soft. Additionally, liquefaction was observed to have taken place at all four sites.

Table 1. SPT N values of the sites investigated prior to cement injection

Depth (m)	Donergecit Building	Karaosman Building	Aydin Center	Atagun Center
1.5	6	9	5	6
3.0	6	8	-	7
4.5	7	39	4	19
6.0	-	61	60	81
7.5	-	17	50	100
9.0	-	15	-	26
10.5	10	33	37	49
12.0	-	40	104	29
13.5	-	40	-	28
15.0	13	55	43	41

Geophysical Investigations

Attempts for evaluating the effectiveness of the cement injection by the SPT tests have not been successful. When the SPT was performed on the cement columns formed , refusal was measured. When the test was done between the columns, SPT N values did not show any appreciable sign of improvement. It was concluded that the SPT is not a suitable method to verify the beneficial effect of the injection process described above.

Columns formed after the injections improve the engineering properties of the global cement-soil matrix. It was decided that the geophysical methods would serve better to evaluate the results of improvement . Possible use of electrical resistivity, georadar, and azimuthal well geophysics methods were evaluated, and the azimuthal well seismic method was adopted.

Azimuthal well geophysics requires that a well is drilled under the building and a geophone is placed inside the well. Explosives are placed in a pit near the building the depth of which is well below the bottom level of the building foundation. The time seismic waves created by the explosives to reach to the geophone is recorded. Since the distance between the source (pit) and the receiver (geophone) is known, velocities of the P and S waves can be calculated. From these velocities, elasticity and shear moduli of the soil are obtained.

Measurements with the azimuthal well geophysics method were made before and after the cement injections and are tabulated in Table 2. The table shows the P and S wave velocities before and after the soil improvement for all four applications. Elasticity modulus and the shear modulus values calculated from the seismic wave velocities are also shown for all four cases for before and after readings.

Table 2. Geophysical measurements before and after the soil improvement

Property	Vp (m/s)	Vs (m/s)	E MPa	G MPa
Donergecit (before)	788	237	2600	900
Donergecit (after)	421	9700	3400	1357
Karaosman (before)	780	231	2500	900
Karaosman (after)	1768	502	14700	5000
Aydin Center (before)	1479	369	6000	2000
Aydin Center (after)	2405	528	17300	5900
Atagun Center (before)	750	290	3500	1200
Atagun Center (after)	1511	475	11300	3900

Table 2 shows that dynamic properties of the treated soil were significantly improved by cement grouting. P-wave velocity increases 1.62 to 2.26 times and S-wave velocity increases 1.43 to 2.17 times. Similarly, the increase in the elasticity modulus is between 2.88 and 5.88 times, and the increase in the shear modulus is between 2.95 to 5.55 times. Improvement in the Karaosman case is very dramatic, because the shear wave velocity has risen from 231 m/s to 502 m/s, causing the soil classification to improve from Group D to Group B. The buildings in an average sized city are usually five storeys high. Improving the soil down to

CONCLUSIONS

It was found based on the four cases reported here that low permeation cement injection is capable of improving the shear wave velocity of the untreated soil approximately twofold and increasing the shear modulus of the untreated soil more than threefold. This improvement in the soil properties may be viewed to heave a serious potential to minimize the liquefaction risk in the treated soil. Applications elsewhere in the world are line with the findings of this study. As a result, it can be concluded that low permeation grouting can be effectively used under existing structures against liquefaction. All other methods are considerable higher costs that prevent home owners from adopting them.

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